MICROMACHINED TWO DIMENSIONAL RESISTOR ARRAYS FOR DETERMINATION OF GAS PARAMETERS

J.J. van Baar, W.A. Verweij, M. Dijkstra, R.J. Wiegerink, T.S.J. Lammerink, G.J.M. Krijnen and M. Elwenspoek

MESA+ Research Institute, University of Twente P.O. Box 217, 7500 AE Enschede, The Netherlands, e-mail: J.J.vanBaar@el.utwente.nl fax: +31 53 489 3343.

ABSTRACT

A resistive sensor array is presented for two dimensional temperature distribution measurements in a micromachined flow channel. This allows simultaneous measurement of flow velocity and fluid parameters, like thermal conductivity, diffusion coefficient and viscosity. More general advantages of measuring temperature distributions are the inherent compensation of heat losses to the support and the insensitivity to variations in the temperature coefficient of resistance.

I. INTRODUCTION

Thermal techniques can be used to measure various fluid and flow parameters[1], like thermal conductivity [2], flow velocity and diffusivity [3], [4], heat capacity, kinematic viscosity and pressure [5]. In this paper a two-dimensional array of resistive heater/sensor structures is presented for simultaneous measurement of flow velocity, thermal conductivity and kinematic viscosity. The paper is organized as follows. First, in section II the basic sensor structure is described. Next, in Section III the fabrication process is discussed. Simulation and measurement results are presented in Section IV.

II. SENSOR STRUCTURE AND OPERATION

Figure 1 shows a schematic drawing of the sensor structure. A two-dimensional resistor array is suspended in a micromachined flow channel using a silicon nitride support structure. The resistors are used for both heating and temperature sensing. Heating is possible by forcing an electrical current through a row of resistors. Temperature sensing is possible for each individual resistor by measuring the temperature dependent resistance value. Three different types of arrays have been fabricated with various numbers of resistors, namely 5x25, 5x9, 18x9.

The measured temperature distribution is a function of the heating pattern, the velocity profile and the type of fluid in the channel. The flow distribution is disturbed by the sensor array, which causes the temperature distribution to be hydrodynamically dependent on fluid parameters. The resistor array acts as a plate separating the channel into two channels. The initial parabolic flow profile is transformed into two parabolic profiles as indicated in Figure 2. The entrance length, i.e. the distance before the flow profile is developed again, is a measure for the kinematic viscosity of the fluid.

An estimation of the hydrodynamic entrance length, $x_{fd,h}$ in the no-slip (continuum) flow regime can be made by calculating the hydraulic diameter D_h and Reynolds number Re_D of the channel [6]:

$$x_{fd,h} = D_h \cdot 0.05 \cdot Re_D \quad \text{for} \quad Re_D < 2300 \tag{1}$$

The Reynolds number Re_D is given by:

$$Re_D = \frac{u_{mean} \cdot D_h}{\nu} \tag{2}$$

with u_{mean} the flow velocity and ν the kinematic viscosity. Thus, measurement of the entrance length and the flow velocity will allow us to calculate the kinematic viscosity.

The entrance length is determined by measuring the heat transfer to the fluid by forced convection as a function of the distance from the leading edge of the plate. When the flow is developed the heat transfer will become constant.

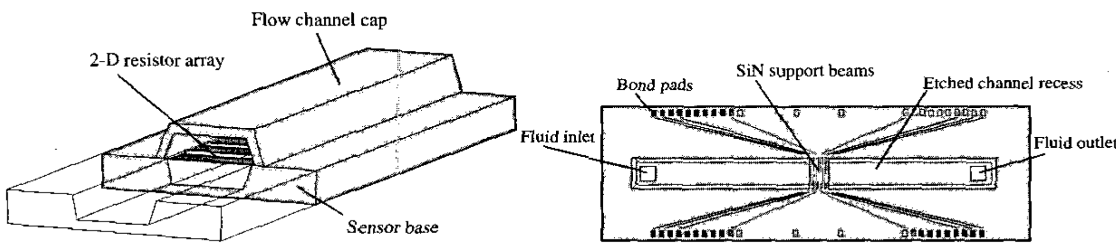

Figure 1. Schematic drawing of the micro sensor with the 2-D resistor array in the center of the flow channel. The channel width is 1 mm. The channel depth below the array and height above the array is 200 μm. The 2-D resistor array is formed by a set of SiN beams, crossing the flow channel, each supporting one row of thin film resistors. Three array versions were realized: I - 5x9 resolution, II - 5x25 resolution and III - 18x9 resolution.

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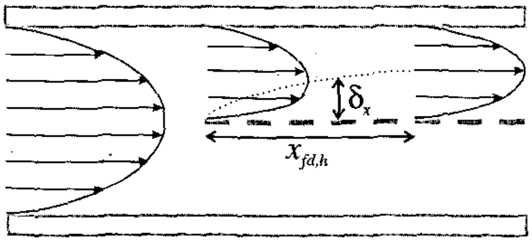
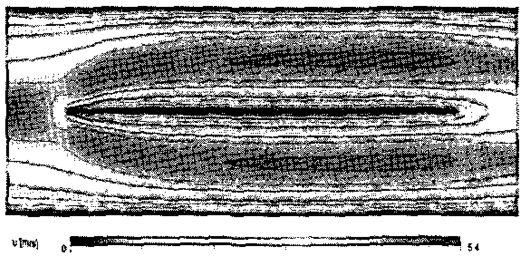


(a) Schematic representation



(b) FEM simulation

Figure 2. Development of velocity boundary layer over the membrane and the hydrodynamic entrance length $x_{fd,h}$.

III. FABRICATION PROCESS

Figure 3 shows a summary of the fabrication process. The first step of the process is the deposition of a 1 µm Si_xN_y layer on a silicon (100) wafer, with a thickness of approximately 380 µm. For a good alignment a special mask structure, in combination with KOH-etching, was used for precisely finding the crystallographic orientation [7]. This step is necessary because of the large aspect ratio of the channel length and width. Misalignment results in a large underetch, which widens the flow channel. The next steps are stripping of the Si_xN_y and the deposition of a 100 nm sacrificial polysilicon layer. The poly silicon layer is needed for underetching the structures crossing the channel. After patterning the poly-Si layer a second Si_xN_y layer is deposited and patterned. Next, a 10 nm chromium primary layer and 200 nm platinum layer are sputtered and patterned using a lift-off process. Finally, the channel is etched in TMAH. In previous devices we used KOH etching [1], but due to the large membrane size the hydrogen bubble formation proved to be a problem. Still, a 2 minute KOH dip was done prior to TMAH etching to remove the native oxide on the silicon. The channel depth is about 200 µm. Figure 4 shows a photograph of a realized device.

A cap is realized in a separate wafer containing only channels with a depth of 200 µm. The cap is glued on the bottom wafer and the devices are broken out of the wafers.

The devices are mounted on an aluminum heat sink with holes for the inlet and outlet. A PCB is placed around the device for making the electrical connections, see Figure 5. After wire bonding the devices are sealed using Permacol SMD glue.

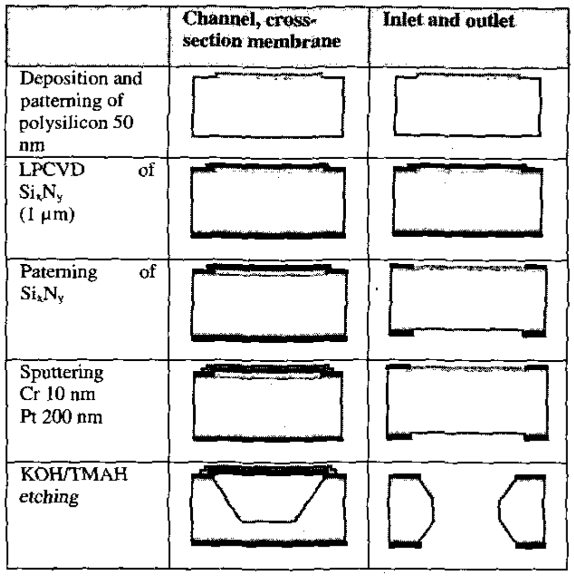


Figure 3. Overview of the fabrication process.

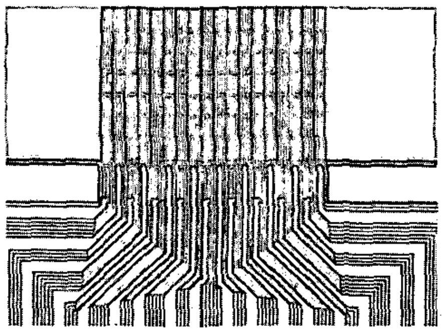


Figure 4. Photograph of the sensor membrane consisting of 18 parallel beams, each having a width of 45 µm. The gap between the beams is 5 µm.

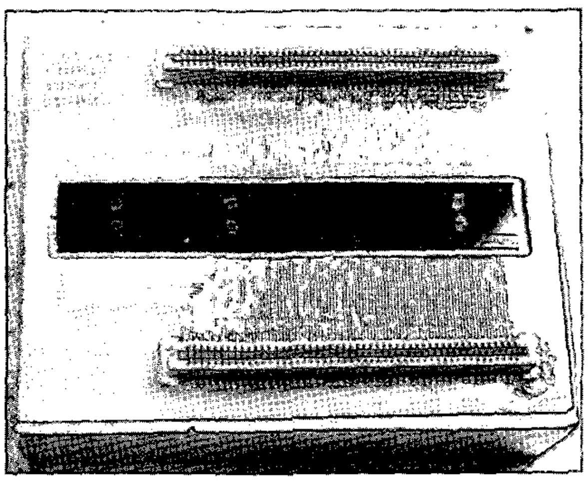
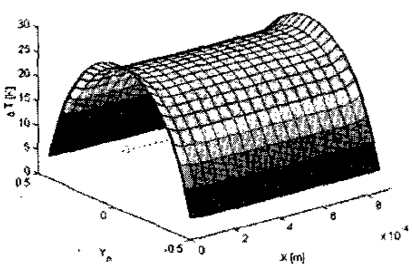


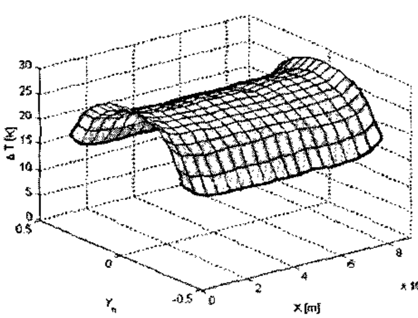
Figure 5. Photograph of a complete sensor just before wire bonding and sealing.

IV. RESULTS

Figure 6 shows the simulated and measured 2D temperature distributions for zero flow. Each beam is heated sequentially and the resulting temperature distribution along the heated beam is measured. The heating current was 2.5 mA. Each beam has a resistance around 105 Ω. This gives a heating power of approximately 0.7 mW per beam. We see that the first and last beams have a slightly higher temperature due to the decreased conduction to neighboring beams. All beams show the typical temperature distribution for heated microbeams [1]. It is determined by conduction through the beams to the support and the conduction through the fluid. This temperature distribution can be used to obtain the thermal conductivity of the fluid.



(a) Simulated

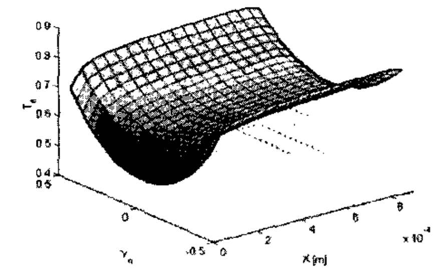


(b) Measured

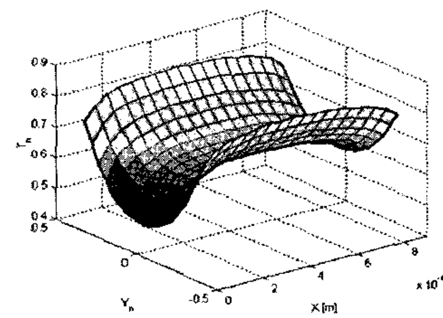
Figure 6 Simulated and measured 2D temperature distributions with zero flow in N_2.

Figure 7 shows the simulated and measured temperature distributions when a flow of 3 m/s is applied. The temperature distribution is normalized; i.e. it is divided by the temperature distribution at zero flow. In this way the influence of the flow is emphasized.

To study the performance of the sensor for measuring the kinematic viscosity several gases were used: Ar, CO_2 and N_2. Because CO_2 has the longest entrance length we used this gas for calibration. The entrance length is obtained from the temperature distribution along the center of the membrane. Figure 8(a) shows this measured temperature distribution for CO_2 at several flow velocities between 1 and 3 m/s. A polynomial fit was made to these curves. The position where the derivative of the fit becomes zero has been taken as the entrance length. Figure 8(b) shows a plot of the obtained entrance length as a function of the mean flow velocity.



(a) Simulated



(b) Measured

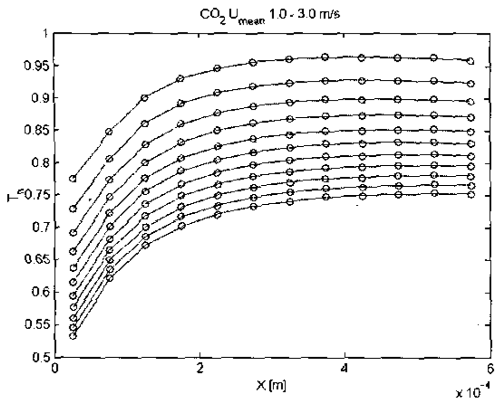
Figure 7 *Simulated and measured normalized 2D temperature* distributions for a mean flow velocity of 3 m/s in N_2. The normalized temperature distribution is the measured temperature profile divided by the temperature profile with zero flow.

The sensor was calibrated by fitting a linear curve based on equation (1) to the obtained entrance length:

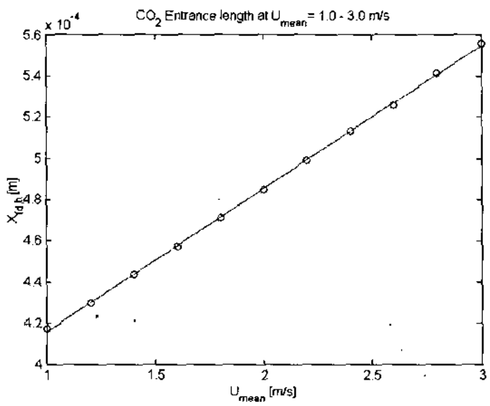
$$x_{fd,h} = A \cdot \frac{u_{mean}}{V} + B \tag{3}$$

The fit parameter A represents the influence of the hydraulic diameter. The parameter B represents an offset due to the fact that we have a flow stagnation point before the membrane and that the first heater is not located exactly at the leading edge of the membrane. The measured $x_{fd,h}$ is clearly proportional to u_{mean}. The maximum deviation from the linear fit is 12 μm. With the known kinematic viscosity of CO_2 the parameters A and B were determined: $A = 5.67 \cdot 10^{-10}$ m^2 and $B = 0.35$ mm.

With the obtained values of A and B, the sensor was used to measure the kinematic viscosity of Ar and N_2. The result is shown in Figure 9. For mean flow velocities above 1.4 m/s the measured kinematic viscosity is within 5% of the theoretical value.

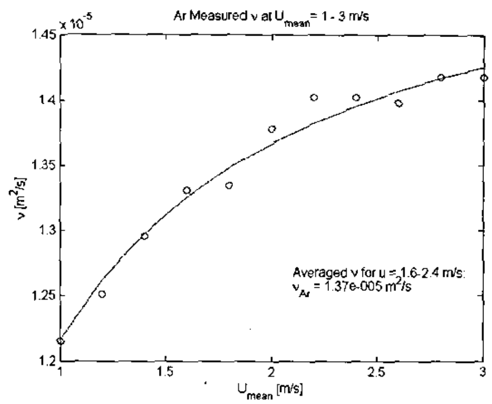


(a) Normalized temperature of the center segment.

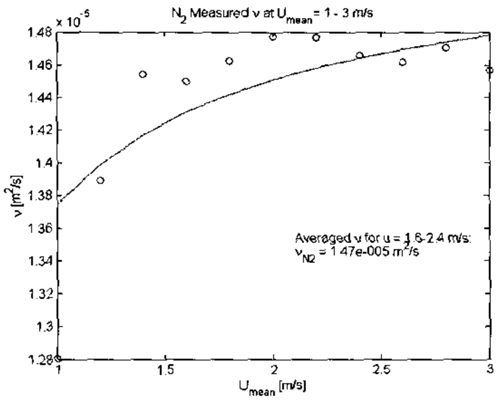


(b) Entrance length as a function of mean flow velocity

Figure 8 Measured normalized temperature of the center segment using CO_2 at mean flow velocities from 1 to 3 m/s (a) and corresponding entrance lengths (b).



(a) Ar



(b) N_2

Figure 9 Measured kinematic viscosity for Ar and N_2 as a function of mean flow velocity using a sensor calibrated for CO_2. The error is less than 5% for mean flow velocities above 1.4 m/s.

CONCLUSION

A resistive sensor array has been presented for two dimensional temperature distribution measurements in a micromachined flow channel. The sensor can be used for determination of the kinematic viscosity. Initial tests with Ar, CO_2 and N_2 show that an accuracy in the order of 5% is obtained. This can be further improved by developing a more accurate model for the sensor. Furthermore, the sensor is in principle suitable for simultaneous determination of the thermal conductivity, however this also requires an improved sensor model.

ACKNOWLEDGEMENTS

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